Observation of terahertz electric pulses generated by nearly filled-gap nonuniform illumination excitation

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Terahertz (THz) electric pulses generated by nonuniform illumination excitation in a nearly filled-gap configuration were observed. In this scheme, the excitation beam is focused to a spotsize only slightly smaller than the spacing between the transmission lines and is located symmetrically within the gap. With 100 fs laser pulses excitation on sliding-contact photoconductive switches fabricated on low-temperature-grown GaAs, electric pulse correlation with 190 ± 20 fs full width at half maximum, which corresponds to a 3 dB bandwidth of 1.1 THz, was observed. Moreover, electric pulses with three times larger peak amplitude than those generated with filled-gap illumination from In coplanar striplines were observed. Bias, wavelength, and pump power dependencies were investigated. © *2000 American Institute of Physics.* [S0003-6951(00)03251-4]

Ultrashort electric pulse generation from laser-excited photoconductive switches (PCS) has been intensively studied because of its various promising applications such as the electro-optical characterization of high-speed devices. PCS may be excited either by uniform (or filled-gap) illumination[1] across the gap or by nonuniform illumination (or edge illumination, asymmetric excitation) near one of the biased transmission lines.[2–6] Unlike filled-gap illumination, the pulse width of the electric pulses generated by nonuniform illumination depends only minorly on the photocarrier lifetime.[2–6] Therefore, special growth or processing steps to reduce the substrate photocarrier lifetimes are not required; excitation and sampling structures can thus be easily incorporated in the substrate along with the devices under test. Nonuniform illumination excitation of PCS fabricated on various substrate materials have been investigated and electric pulses as short as 200, 250, 350, 550, and 800 fs full width at half maximum (FWHM) from low-temperature-grown (LT–) GaAs,[3,4] silicon-on-sapphire,[2] InP,[6] and Si[6] substrates, respectively, have been reported. With nonuniform illumination, it was found that the generated electric pulses depends strongly on the size and location of the pump beam.[3–7] To make use of the electric field singularity, it is also customary to focus the excitation beam tightly on the area close to the positively biased transmission line. In this letter, we report our observation of electric pulses as short as 190 fs FWHM generated by a symmetric nearly filled-gap nonuniform illumination (NFGNI) geometry. Moreover, we found that the peak amplitude of the NFGNI generated electric pulses from In coplanar striplines (CPS) is three times larger than those due to filled-gaped illumination excitation.

Our PCS were fabricated on LT–GaAs layers, grown by molecular beam epitaxy on 2 in. (100) semi-insulating GaAs substrates. These LT–GaAs samples consist of a 0.4 μm GaAs buffer layer, a 0.5 μm AlAs layer, both grown at 600 °C, and a 1.2 μm LT–GaAs layer deposited at 220 °C. Typical growth rate was 1 μm/h and an As_4/Ga beam equivalent pressure of 25 was maintained during the growth. These LT–GaAs samples were annealed *in situ* under As_4 flux at 600 °C for 20 min immediately after the growth. These LT–GaAs layers were previously characterized with time-resolved photoreflectance as well as transient photoconductive measurements, and a photocarrier lifetime around 270 fs was measured.[8] Detailed substrate preparation and growth parameters can be found in Ref. 9.

Sliding-contact PCS made of In CPS were patterned by photolithography on the LT–GaAs samples. Both the metal linewidth and the spacing are 20 μm, which correspond to a characteristic impedance of 91 Ω.[10] The photoconductivity measurement setup is a conventional pump-probe configuration with both the excitation and sampling beams derived from a Tsunami pulsed Ti–sapphire laser system. Typical pulse width and excitation (sampling) power were 100 fs and 60 mW (10 mW), respectively. The excitation beam was chopped at 100 Hz and the voltage across a load resistor by the photocurrent was detected with a lock-in amplifier. Change in the voltage was recorded as a function of the time delay between the excitation and sampling pulses.

In the NFGNI scheme, the excitation beam is focused to a spotsize slightly (roughly 5%) smaller than the spacing between the transmission lines, and is located symmetrically within the gap. Both the excitation and the sampling gaps are excited with NFGNI. The measured photoconductive response is therefore the cross correlation of the electric pulse generated at the excitation gap with that at the sampling gap.

Figure 1 shows the photoconductive response of the CPS biased at 15 V excited in the NFGNI scheme. To avoid complication due to dispersion effects, the generated electric pulses were sampled at zero propagation distance; that is, the excitation site is located directly above the sampling finger.

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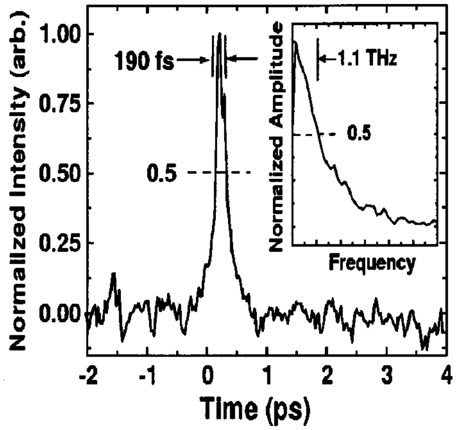

FIG. 1. NFGNI excited ultrafast electric pulse with FWHM of 190±20 fs. The spectrum of the electric pulses is shown in the inset, and 3 dB bandwidth of 1.1 THz was achieved.

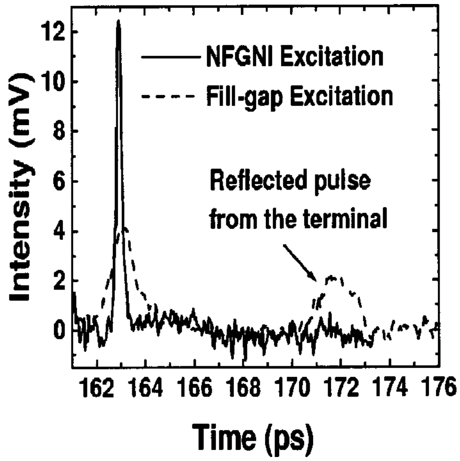

FIG. 2. The comparison of electric pulses generated with NFGNI and filled-gap excitation. The base lines have been removed for clarity. Note that the peak amplitude of the NFGNI excited electric pulse is three times larger than that by filled-gap excitation.

For clarity the whole trace was adjusted vertically and the peak was normalized to one. An electric pulse correlation with 190±20 fs FWHM, which corresponds to a 3 dB bandwidth of 1.1 THz, was observed. Note that the electric pulse is free of trailing shoulder. It is also remarkable that our correlation sampling measurement has produced the same time resolution as that obtained from electro-optic measurement.[5] The fact that the pulse width is shorter than the photocarrier lifetime is an evidence that nonuniform illumination is the dominant excitation mechanism.

Among the various models to explain the ultrafast electric pulse generation by nonuniform illumination,[2–4,11–15] it is generally accepted that the displacement current due to the redistribution of the photocarriers plays a major role.[11–15] In this theory, the generated photocarriers redistribute themselves to screen out the applied electric field in the illuminated area and result in very fast displacement current pulses. We believe that displacement current is also dominant in the case of NFGNI excitation. Moreover, we note that in conventional nonuniform illumination with asymmetric excitation geometry, the temporal evolution of the local surface field peaks most steeply at the edge of the illuminated area (Fig. 3 in Ref. 14 and Fig. 5 in Ref. 4, for example); it is therefore not surprising that very short electric pulse was observed with NFGNI excitation. It is also notable that the electric pulse is free of trailing shoulder, even though the electric pulse is sampled at zero propagation length. The absence of trailing shoulder is consistent with the shoulder-free electric pulse observed by Alexandrou *et al.*[4] at the edge of the excitation spot.

Figure 2 shows the photoconductive response of the same CPS excited with NFGNI and filled-gap illumination, respectively. In the latter, both the excitation and sampling gaps were excited with filled-gap illumination. Except for the beam size, both traces were taken under identical experimental conditions. For ease of comparison, the base lines of both of the traces have been removed. The difference in pulse width indicates again the different excitation mechanisms between these two cases. Note that, in contrast to conventional nonuniform illumination for which the peak amplitude of the electric pulses is usually smaller than that due to filled-gap illumination, the peak amplitude of the NFGNI excited electric pulses is three times larger. Since the transit time across the interelectrode spacing is at least hundreds of picoseconds and the electric pulses is dominated by the initial change in electric field, the absence of photoconductive gain in LT–GaAs due to its short photocarrier lifetime alone cannot explain this large NFGNI peak amplitude. A possible explanation may be obtained by noting that the NFGNI leads to symmetric electric field distribution within the spacing, with field singularities close to the electrodes. This field distribution resembles closely the transverse electric field of the CPS propagating mode [see, for example, Fig. 6(a) in Ref. 16]. High coupling efficiency is therefore expected. It is also noteworthy that while the reflected pulses from the end of the transmission line clearly show up for filled-gap illumination, they are absent in the NFGNI case. This was attributed to the much stronger dispersion effect of transmission line at high-frequency.[4–6] We noted that these strong electric pulses generated by NFGNI from In CPS were not observed from Au CPS on similar LT–GaAs layer. We speculate that this might be due to the inadvertently less contrast in reflectivity between Au and LT–GaAs substrate, which we employed to position the excitation beams. More elaborate scheme to position the beam is under investigation.

The effects of wavelength, pump power, and bias voltage on the NFGNI excited photoconductive response were investigated and the results were shown in Fig. 3. Except for the parameters shown, all these traces were taken under identical conditions. The peak amplitudes and the backgrounds of these NFGNI excited photoconductive response were plotted with respect to the bias voltage in Figs. 4(a) and 4(b). We note that at higher bias voltage (30 V), the base line prior to the peak does not coincide with the trailing background; for such cases the prior base line was taken as the background, from which the peak amplitude was measured.

From Fig. 4(a), we found that the bias voltage has the dominant effects on the peak amplitude. The peak grows higher as the bias voltage increases. Though not shown here, by replotting the relationship in log–log scale, we found that the peak amplitude seems to grow in proportion to the 3/2 power of the bias voltage. This is to be compared with the nonlinear relationship previously observed for conventional nonuniform illumination.[4,5]

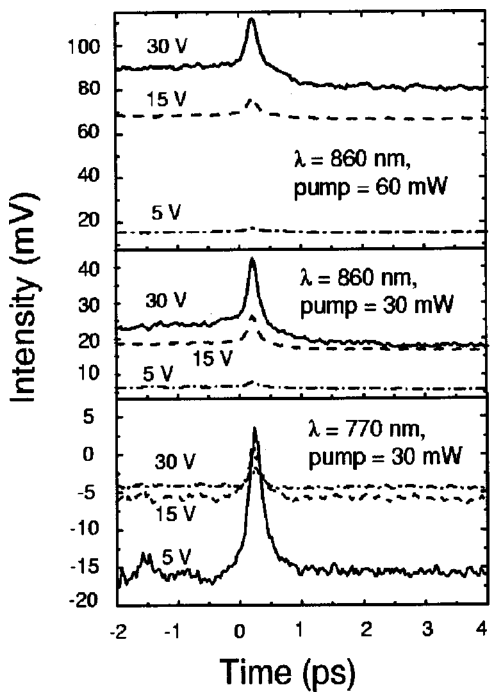

FIG. 3. The NFGNI excited electric pulses taken at different wavelengths, pump power, and bias voltage. It is to note that the vertical scales in these three plots are not the same and that these traces were the originally measured data with their base line unadjusted.

Unlike bias voltage, the wavelength and the pump power were found to have little effect on the peak amplitude. This is different from the case of conventional nonuniform illumination in which the amplitude of the generated electric pulses depends on the excitation wavelength[5,11] and is linearly proportional to the pump power.[5] This weak pump power and wavelength dependencies of the NFGNI generated electric pulse amplitude do not comply with the displacement current model. It is not clear to us at this moment whether these weak dependencies hold also for substrates other than LT–GaAs. Further studies are required to clarify the underlying excitation mechanisms.

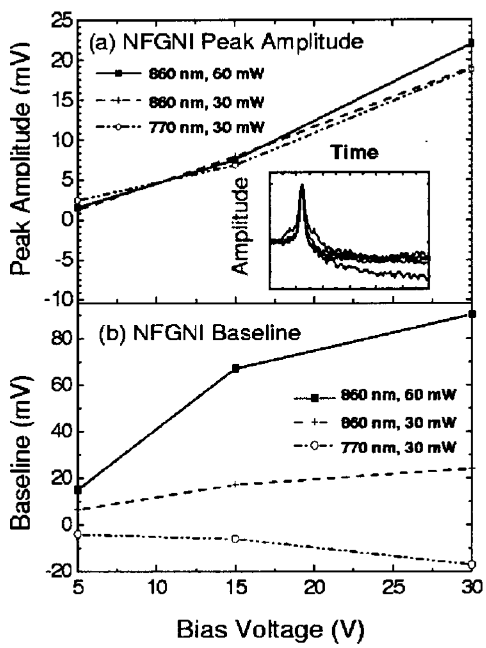

FIG. 4. (a) The amplitude and (b) the background of the NFGNI excited electric pulses as functions of the bias voltages. The inset in (a) shows the normalized traces in (a) and (b), indicating roughly the same FWHM.

From Fig. 4(b), the background was found to depend strongly on bias, wavelength and pump power. For longer wavelengths (860 nm), the background increases as the bias voltage increases; whereas for shorter wavelength (770 nm), the background decreases as the bias voltages increases. The excitation wavelength affects both the density of the photocarriers, which determine the dielectric relaxation process, and the penetration depth, which affects predominantly the diffusion and redistribution of the photocarriers. Moreover, the electron and hole conduction current components as well as the recombination of photocarriers can also contribute. Quantitative modeling is thus required to elucidate these observed dependencies.

Though the amplitude and background of the traces in Figs. 4(a) and 4(b) depends on all three parameters we discussed, we found that their peak can all be normalized to the same curve [the inset in Fig. 4(a)]. The dependence of the FWHM of the electric pulses on wavelength, pump power, and bias voltage is therefore quite weak. We have also changed the polarization of the optical beams and found no significant effect. The effects of contact metals and substrate materials are also under investigation. The results will be reported elsewhere.

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